Parameterization of a Two-Phase Sheet Flow Model and Application to Nearshore Morphology

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LONG TERM GOAL

The overall objective is to develop and test with laboratory and field observations a model that predicts sediment transport and morphological change in the nearshore for a range of wave conditions and sediment characteristics.

OBJECTIVES

The specific objectives of this project are to

1. parameterize the wave-induced bottom stress and sediment transport rate using a two-phase sheet flow model

2. couple the sediment transport model with a time-domain Boussinesq hydrodynamic model to predict beach profile evolution

3. improve the two-phase sheet flow model by comparing its predictions with laboratory and field observations of sediment transport.

APPROACH

A two-phase sheet flow model [*Hsu et al.*, 2004; *Hsu and Hanes*, 2004] was utilized to study and parameterize the time-dependent sediment transport rate under field observed wave forcing in the

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surfzone at Duck, NC [e.g., *Elgar et al*., 2001]. According to the two-phase model results, we conducted rational parameterizations for flow turbulence, particle intergranular stresses, and fluid-sediment interactions and proposed simplified approaches for wave induced transport. The simplified approaches are first tested by driven with field measured forcing to predict observed nearshore sandbar migration events. Effective approaches for sediment transport rate are further incorporated into a Boussinesq wave model (FUNWAVE, see *Kirby* [2003] for an overview of applications) to predict surfzone hydrodynamics, sediment transport and beach profile evolution given field measured offshore wave condition and initial bathymetry.

WORK COMPLETED

The two-phase model is driven by field observed wave forcing measured in the surfzone at Duck, NC. Specific attention is focused on the dynamics between the wave forcing and the resulting bottom stress and transport rate. According to the two-phase model results, several simplified approaches, when driven by the field measured wave forcing, were shown to be capable of modeling an observed 5-day onshore sandbar migration event. These simplified parameterizations are further incorporated into a Boussinesq wave model FUNWAVE. FUNWAVE has been coupled to a bottom boundary layer model which is run at a fine spatial resolution in the cross-shore to calculate an instantaneous bottom stress, followed by a transport rate based on the Meyer-Peter Mueller formula. Transport is then averaged for 10's of minutes and then used to update the bottom at a more appropriate morphological time step. Calculations based on a mixing length closure and linearized boundary layer equations have been completed. Given the field measured offshore wave conditions and initial bathymetry, the Boussinesq model is able to reproduce both the observed surfzone hydrodynamics and beach profile evolution during an onshore sandbar migration event. This year, work has been done to provide a stable numerical scheme for long term morphology calculation, and to better incorporate undertow effects in the Boussinesq model in order to better represent erosional events, where undertow provides a major part of the hydrodynamic signal leading to net sediment transport [*Gallegher et al,* 1998].

This year, the assumptions adopted in the simplified sediment transport approaches are further tested with field data measured in the inner surf zone and swash zone during SwashX [*Raubenheimer 2002*]. As summarized in *Hsu and Raubenheimer* [2005], the assumption that the phase-lag between the free-stream velocity and bottom stress is negligible may not be appropriate in the inner surf zone and swash zone. On the other hand, the assumption that the sediment transport rate is in-phase with bottom stress may be plausible for typical beach sand ($d>\approx 0.18$mm) unless strong breaking wave turbulence affects the bottom sediment transport. According to further analysis on the detailed velocity and free-surface time series measured during SwashX, it is concluded that the surface-generated turbulence due to broken wave often touches down and enhances bottom boundary layer turbulence. When the ratio of water depth to RMS wave height is smaller than about 2, the effects of breaking wave turbulence on near bed sediment transport must be included. Progress has also been made to further extend the two-phase model to simulate transport of finer sand. Preliminary model-data comparison with U-tube data measured by *Dohmen-Janssen et al.* [2002] and *O'Donoghue and Wright* [2004] suggest that the refined closure for turbulence-sediment interactions calibrated by the DNS results [*Squires and Eaton*, 1994] is promising.

RESULTS

Previously, *Long et al [2004]* have shown that a modeling approach using the Boussinesq model FUNWAVE together with a simple linearized boundary layer model and the Meyer-Peter Mueller sediment transport formulation was capable of modeling the onshore migration of a shore-parallel bar

in the period from September 22 to 29, 1994 during the Duck '94 field experiments. These successful simulations were constrained only by the measured bathymetry at the start of the week-long simulation, and by the forcing provided by measured incident waves (with spectra updated at 3 hour intervals) and tide elevation. In order to extend simulations to cover longer time periods, in particular to cover erosional events, it was necessary to (a) address the issue of long term stability in numerical estimates of bed-level change, and (b) incorporate a parameterization for roller volume flux in the Boussinesq model in order to accurately mimic undertow effects during energetic breaking wave events.

A stable framework for doing calculations of morphology evolution has been developed using several variants of the WENO (weighted essentially non-oscillatory) scheme [*Liu et al, 1994*]. We have developed solutions of the bed evolution equation using WENO schemes for spatial differencing, together with time differencing using either Euler forward differencing, or a more sophisticated TVD-RK (total variation diminishing – Runge Kutta) scheme [*Shu and Osher, 1988; Shao et al, 2004*]. In practice, we have found that the WENO scheme provides stabilization of the solution for bed form evolution for either choice of time-stepping. We therefore presently use the Euler scheme in view of its much greater simplicity. The scheme has been tested in comparison to the Lax-Wendroff scheme (with or without the additional filtering developed by *Johnson and Zyserman* [2000]), a two-step Lax scheme due to MacCormack, and the Warming-Beam upwind scheme. The resulting calculations demonstrated that the Euler-WENO scheme is less prone to development of spurious oscillations and exhibits less numerical diffusion than the other tested schemes. The scheme performs as well as the more complex Roe scheme tested recently by *Hudson et al* [2005], and is easier to implement in two horizontal dimensions since it does not require the estimation of a parameter related to the characteristic form of the governing equation.

Figure 1 shows several snapshots in time of the evolution of an alternating bar in a stream of initially rectangular cross-section. Initial instabilities in this configuration are sinusoidal along the channel and, for the lowest mode, are a half-cosine across the channel. The bed form grows and evolves over time into a more complex form characterized by a pronounced, oblique shock structure separating bar crests (red) from troughs (blue) on downstream-facing zero-crossings. Previous calculations with high-order spectral methods [*Gungordu and Kirby,* 2000] for the same geometry have shown a tendency to develop short oscillations in the neighborhood of the shocks, indicating the robustness of the present finite difference approach.

The stability of the Euler-WENO bed-evolution scheme has led us to adopt this approach as the standard seabed module in the NearCoM model system, where it is used in conjunction with both wave-resolving and wave-averaged circulation model schemes. Further details will be presented in *Long et al* [2005].

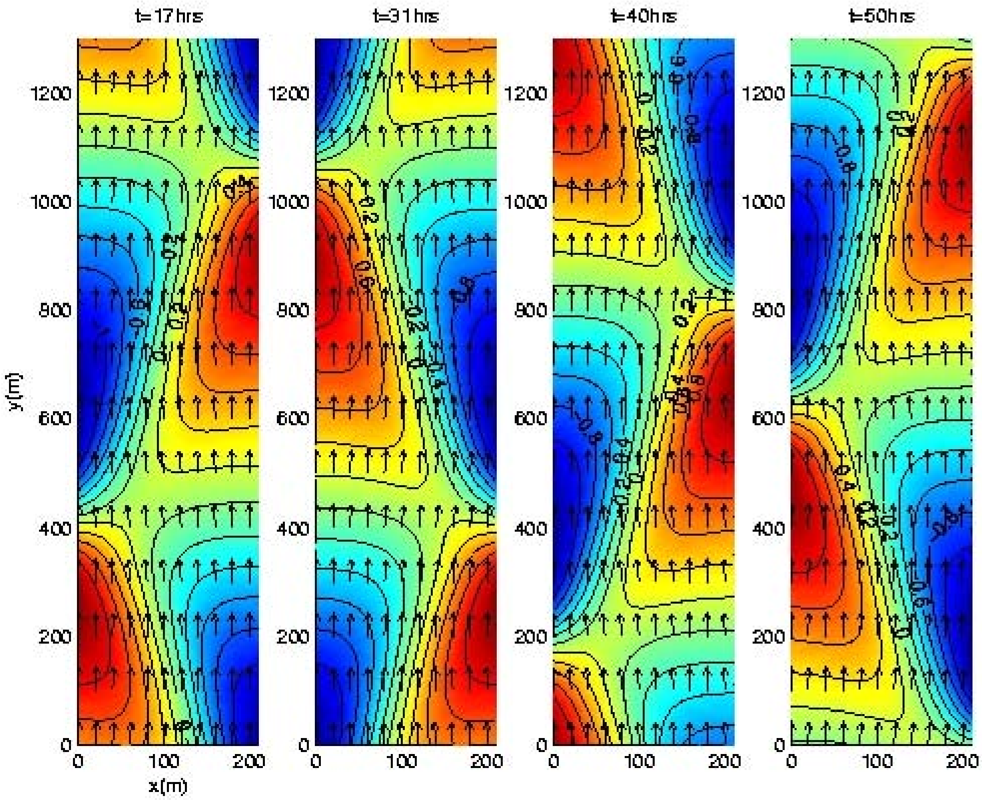

Figure 1. Snapshots of a downstream-propagating alternating bar system in a straight, rectangular channel. Red indicates bar crests. Bar crests and troughs are separated by an alternating oblique shock structure which evolves as a smooth feature in the Euler-WENO computational scheme used for morphology calculation. In each panel, flow is from bottom to top.

The need for a better representation of undertow in the Boussinesq model has led to a reformulation where the profile of horizontal velocity is explicitely divided into an irrotational component and a roller component. The resulting formulation is reminiscent of the roller formulation of *Schaffer et al* [1993], but with retention of the eddy viscosity formulation, full nonlinearity, and extended dispersion used in FUNWAVE. A test of the undertow predictions for regular waves shoaling and breaking in a laboratory flume are shown in Figure 2 in comparison to measurements from *Stive and Wind* [1986]. In this simulation, modeled wave height is somewhat overestimated in the surfzone, but undertow below wave trough level and mean setup are represented accurately.

Due to strong undertow current, accurate prediction of beach erosion requires an effective bottom stress parameterization for combined wave-current flow. Models that simultaneously resolve the wave and current boundary layers using the RANS equation capture the nonlinear wave-current interactions and provide accurate bottom stress [e.g., Davies et al. 1988; Henderson et al. 2004]. However, it is time-consuming to couple these wave-current boundary models directly [Henderson et al. 2004] with wave hydrodynamic models for a predictive tool of beach morphology. Under a combined wave-current forcing, the computational requirement for the RANS boundary layer model is significant because the horizontal pressure gradient (energy slope) required to achieve the desired current velocity is not known as a priori [Grant and Madsen 1979] and an iteration procedure is often needed [e.g., Davies et al. 1988]. On the other hand, given a time history of near-bed flow velocity, it is efficient to

simply calculate the bottom stress induced by pure oscillatory forcing using either boundary layer equations or momentum integral method [Fredsoe, 1984]. For the purpose of sediment transport, we investigate an efficient and accurate phase-resolving parameterization for bottom stress under wave-current interactions.

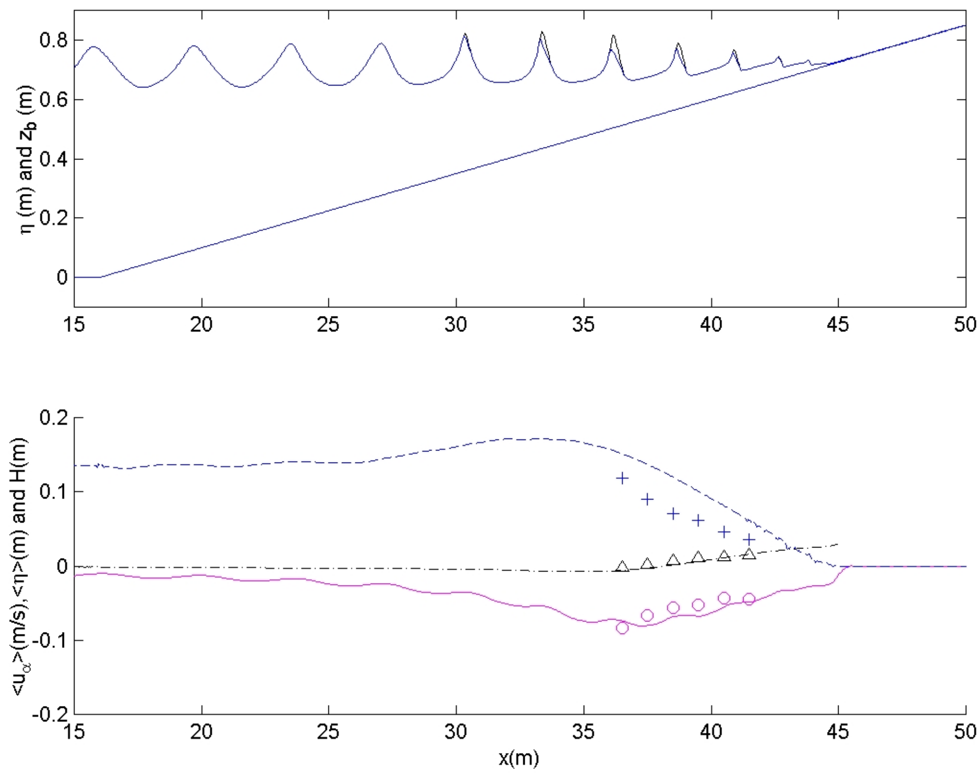

Figure 2. Model predictions of wave height, mean water level setup, and undertow below trough level for monochromatic wave experiments of Stive and Wind [1986]. Top panel shows a snapshot of the resolved wave field and indicates roller geometry at the crests of breaking waves. The model is seen to overpredict breaking wave heights relative to data (crosses), but setup (triangles) and undertow(circles) are accurately reproduced.

Using a validated boundary layer model *[Hsu, submitted]* that calculate RANS equation with *k-ε* closure driven by several laboratory and field measured random wave forcing, a new parameterization of bottom stress under combined wave and current flow is proposed. The nondimensional bottom stress $\theta(t)$ is parameterized by the bottom stress driven by pure wave $\theta_w(t)$ and pure current $\theta_c(t)$:

$$\theta(t) = \theta_c + \theta_w(t) + C_1 |\theta_w(t)| \frac{\theta_c}{|\theta_c|} + C_2 |\theta_c| \frac{\theta_w(t)}{|\theta_w(t)|} \tag{1}$$

with *C1* and *C2* as empirical coefficients. The 1st and 2nd terms of (1) are contributions to bottom stress from pure wave and pure current while the rest of the terms represent nonlinear wave-current interactions. Specifically, the magnitude of the 3rd term $C_1 |\theta_w| \theta_c / |\theta_c|$ is proportional to the strength of the wave contribution $|\theta_w|$ with its direction following the current $\theta_c / |\theta_c|$. This term can be considered

as the effect of waves on the mean current. Here, the magnitude of such an effect is time-dependent. However, after time-averaging, this term provides an enhancement to bottom friction following the current direction and is consistent with the "apparent roughness" concept [Grant and Madsen 1979]. The 4th term $C_2|\theta_c|\theta_w/|\theta_w|$ has a magnitude that is proportional to the strength of the mean current and a direction following the wave. This term represents a nonlinear contribution to bottom stress that enhances the pure wave induced bottom stress $\theta_w(t)$ when the wave and current flow in the same direction but reduces $\theta_w(t)$ when they do not flow in the same direction. The 4th term can be considered as the effect of the mean current on waves. Equation (1) and the empirical coefficients have been tested extensively for variously cross-shore wave condition (simple sinusoidal or random waves with different magnitudes of current). Here, equation (1) is further demonstrated to be effective even when strong alongshore flow also present (However, empirical coefficients also depend on alongshore flow intensity. This is not further discussed here.). Concurrently measured cross-shore $U_0(t)$ and alongshore $V_0(t)$ near-bed flow velocities (figure 2a) during Duck94 field experiment (e.g., Elgar et al. 2001) are utilized to drive a RANS boundary layer model with *k-ε* closure. Numerical model results for bottom stress $\theta(t)$ and residual stress $\Delta\theta(t) = \theta(t) - (\theta_w(t) + \theta_c)$ (used here to quantify the nonlinear wave-current interaction) are considered here to be the "true" solutions that represent nonlinear wave-current interaction accurately (solid curves in figure 3c and 3b). The parameterized time-dependent bottom stress using (1) is obtained by calculating $\theta_w(t)$ using results obtained by another model runs driven by only the pure wave forcing and θ_c using the logarithmic law for a steady current over a rough bottom. The parameterized bottom stress (dashed curves in figure 3c) is similar to that directly calculated by the numerical model with relative error 0.13. The square correlation of $\Delta\theta(t)$ between the numerical model results and that parameterized by equation (1) is 0.57. Notice that if using only the "apparent roughness", the parameterized $\Delta\theta(t)$ reduces to a constant and its correlation with that obtained directly from the numerical model is zero. Results shown here are for rather large alongshore flow condition. The performance of (1) is further increased when the alongshore flow is weak.

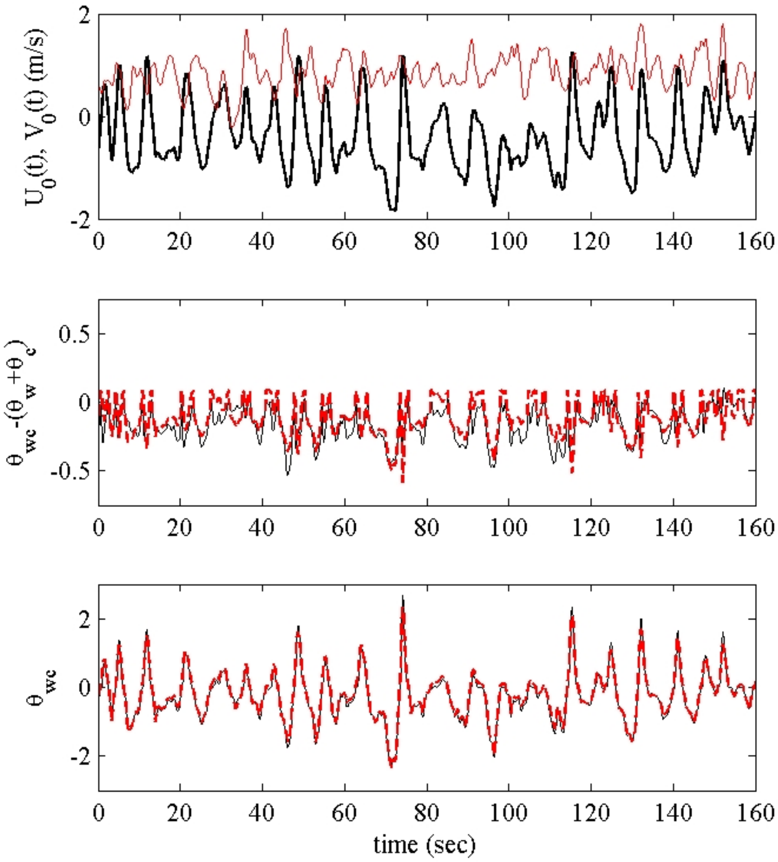

Figure 3: The bottom stress (c), residual stress (b) calculated by the numerical model (solid curves) and the new parameterization (equation (1), dashed curves) driven by (a) field measured nearbed cross-shore U0(t) (thick curve) and alongshore V0(t) (thin curve) velocities near a sandbar crest during the Duck94 field experiment [Elgar et al. 2001]. The mean current and R.M.S wave velocities are Uc = -0.27m/s, Urms = 0.70m/s, and Vc = 0.88m/s, Vrms = 0.33m/s, respectively. The new parameterization predicts the "true" cross-shore bottom stress reasonably well (relatively error 0.13) even under rather strong alongshore flow. The square correlation of residual stress between the numerical model results and that parameterized by (1) is 0.57. This correlation is would be zero if the nonlinear wave-current interaction is parameterized by a constant value of apparent roughness.

IMPACT/APPLICATIONS

The use of the two-phase model with field measured forcing enhances our physical understanding on sediment transport and provide rational approach to develop simple and effective sediment transport parameterizations. The coupled Boussinesq-sediment model, when further comprehensively tested with field and laboratory data, is the first step toward developing a physical-based predictive model for large-scale nearshore sediment transport and shoreline change. The development of a robust numerical scheme for bed morphology evolution benefits the field of morphology modeling at all scales.

RELATED PROJECTS

Field data collected during Duck94, SandyDuck and SwashX is extensively used to guide the development and calibration of the models.

The NOPP project “Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean” has developed the model system NearCoM, which uses FUNWAVE as one of it's circulation model components. The code for computing morphology evolution resulting from this study now serves as the seabed module for both wave-averaged and wave-resolving formulations in NearCoM.

Both PIs Hsu and Kirby are involved in a collaborative research project CROSSTEX for surfzone hydrodynamics, sediment transport and morphological evolution. The laboratory experiment was conducted in Summer 2005 at O.H. Hinsdale Wave Research laboratory of Oregon State University. The major modeling components for the CROSSTEX were proposed by Hsu (Co-PI: John Trowbridge) to ONR Coastal Geoscience Program. Kirby is taking part in long term morphology change tests, which will be used to test model predictions made with the models being developed here. (This work is presently being done by UD student Pablo Teran). The sediment transport parameterization and model development conducted in this research will be influential to the CROSSTEX project.

Hsu and Raubenheimer (WHOI) collaborated via a NSF grant (CTS-0426811) to Woods Hole Oceanographic Institution to study sediment transport in the inner-surf and swash zone. Field data measured during SwashX was made available to the present project through this collaboration.

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(two additional manuscripts, covering the incorporation of undertow in the Boussinesq model, and the use of that model to predict cross-shore profile evolution during Duck 94, will be written based on Wen Long's dissertation, due for completion during October 2005).